Saskatchewan
Agriculture
and Food

ADF

AGRICULTURE DEVELOPMENT FUND

FINAL REPORT

20030549

IDENTIFICATION OF REPRESENTATIVE BENCHMARK SITE FOR SOIL SAMPLING

Funded by: The Agriculture Development Fund

August 2007

Prepared by: University of Saskatchewan

Final Report (April, 2007)
Project #20030549

Title: Identification of representative benchmark site for soil sampling

Dr. Bing C. Si and Dr. Jeff Schoenau
Department of Soil Science, University of Saskatchewan
April, 2007

Table of contents

Abstract

Soil moisture is a major limiting factor for crop production in the Canadian prairies. The strong spatial variability in field soil water makes it difficult to select representative benchmark sites. The main objective of this project was to develop a new approach for identifying a representative bench mark site in a farm field utilizing the spatial patterns of soil water distribution and crop yield in the field. To achieve this objective two representative sites have been selected within Saskatchewan. Results indicated that representative benchmarking is possible, but a priori identification of representative benchmarking site requires further research.

General Summary

The project was initiated in May 2004 and has been funded through the Agriculture Development Funds of Saskatchewan. The main objective of this project was to develop a new approach for identifying a representative bench mark site in a farm field utilizing the spatial patterns of soil water distribution and crop yield in the field. To achieve this objective four representative sites have been selected within Saskatchewan and several research activities are being conducted. We investigated if (1) it is possible to identify benchmark sites from measured soil water content, (2) what are the best landscape positions that represent the average behavior of the soil nutrients and crop yield, and (3) Which topographic parameters best represent the spatial variability of soil water and crop yield. Results indicated that the representative benchmark site can be selected from rolling landscapes. The midslope best represented the average behavior of soil nutrients and crop yield. And contributing area is the best crop yield indicator in a rolling landscape. In the following, we summarize the three detailed studies from two hummocky landscapes in Saskatchewan:

1. The first study examines if there is a persistent patterns in soil water storage and if a representative benchmark site can be identified from an undulating landscape (Alvena, Saskatchewan). Results indicated that there were no persistent patterns in soil water storage (0-40 cm). However, there was a location that consistently represented the average soil water storage in the landscape. This position was on a north-facing midslope.
2. The second study examines if it is possible to identify the landscape slope positions (or land elements) that best represent the average behavior of the field soil properties and crop yield and thus can be used as benchmark sites of soil fertility in a gently sloped landscape (Centre Butte, Saskatchewan). Results indicated that there was no single location that can be used as representative site for soil fertility and crop yield. However, back slope positions were the best indicator of average soil fertility and crop yield for 2005 and divergent slope for 2006.
3. The third study examines which topographic and soil properties indicator best represents the spatial variability of soil water and wheat yield in an undulating landscape of Alvena, and Hepburn, Saskatchewan. Results indicated that the contributing area outperformed the relative elevation and was the best wheat yield indicator. In extremely wet years, the contributing area is negatively correlated to wheat yield and in average and dry years, the contributing area is positively correlated to wheat yield. Therefore, the contributing area may be a possible indicator for finding representative benchmark sites for soil water and crop yield. However, this finding may apply to fields with large depressions and knolls.

Therefore, at Alvena, it is possible to identify representative benchmark sites. In the gently rolling landscapes (Centre Butte), it is not possible to identify a single location as the representative benchmark site; however, back slope is the best representative landscape position for benchmarking. The benchmark landscape position changes between 2005 and 2006. Benchmarking has been used by WestLab and selection of benchmark sites is empirical and can be arbitrary. This study suggested that benchmark sites should be selected based on the spatial patterns of soil water and crop yield. However, this requires monitoring many locations within a

field. With the advancement of new technology (such as yield monitor and remote sensing), the proposed representative benchmarking method can be very useful in fertilizer recommendations, and fertility monitoring for effective management.

Sites and Methods

In order to characterize the spatial and temporal patterns of soil water storage and redistribution under different topography and soil conditions four representative sites have been selected within Saskatchewan and several interrelated research activities are being conducted. The sites are Alvena (Orthic Black Chernozemic soil with silty clay loam texture), St. Denis (Dark Brown soil with loamy texture), Laura (Orthic Dark Brown Chernozem with a silt loam texture), and Central Butte (Brown Chernozemic soil).

At the Alvena site a 620-m transect was established and continuous measurement of soil water was conducted at 103 locations using a capacitance probe technique. To this end access tubes were installed (160 cm deep) every six meter along the transect. Besides the capacitance readings, neutron probe readings and gravimetric samples were repeatedly used to obtain a good calibration curve and improve accuracy and reliability of measurements. Part of this program included snow sampling and continuous yield monitoring.

At the Laura site a grid of 50 monitoring locations were established in 2005. Gravimetric samples were taken for determination of soil water content. 51 Diviner tubes were also installed. However, the farmer forgot the tubes in the field and destroyed all the tubes while he performed a tillage operation on the field. Therefore, the site was discontinued in 2006.

At the St. Denis site a 128 m transect was established and sampled every 4.5 m. At this site soil moisture and CO_2 flux was monitored continuously. Capacitance probes, time domain reflectometry, and gravimetric methods were used at the site. Because 2004, 2005, and 2006 were very wet years and a third of the access tubes were under water (tubes in depression), only partial data was obtained from the St. Denis site.

At the Central Butte site a 210 m transect was established and sampled every 7 m. Soil water measurement of this site was conducted using time domain reflectometry and gravimetric methods. Samples collected from this site were also analyzed for nutrient contents in 2005 and 2006.

Study I. Identification of Representative Soil Water Benchmarking

1.1 Summary

Soil moisture is a key hydrological factor affecting the fate and transport of pollutants in soils as well as greenhouse gas emissions. There is strong spatial variability in field soil water, which requires monitoring many locations to capture the salient features of soil water in the field. The objective of this study was to examine whether there are temporally stable soil moisture patterns in a field and whether a representative moisture benchmark site can be identified from these patterns. The experiments were conducted on a black soil at Alvena, northeast of Saskatoon, Canada. Soil moisture was monitored at 95 measurement sites using the gravimetric method along a 612 m rolling transect, from April to September in 2001and 2005. Temporal stability of

spatial patterns in soil storage from 0 to 40 cm depth were determined using temporal means and standard deviations of the differences between individual and spatial average values of soil moisture along the transect. The spatial patterns of soil water storage were stable in different locations for each depth. Contrary to reports in the literature, clay content showed the least amount of control on spatial patterns. Coefficient of variation and standard deviation of soil moisture both decreased with increasing soil moisture. Soil moisture benchmark sites identified in this study represent field mean soil moisture and can be used for environmental monitoring and modeling.

1.2 Introduction

Soil water is the principle limiting factor in semi-arid agricultural production and a key element in environmental health. Soil water also affects the transport of sediment, toxins and chemicals to environmentally sensitive areas such as surface water bodies and ground water. In addition to flowing water, antecedent soil moisture has an effect on water infiltration, percolation to lower depths, runoff and evapotranspiration (Gómez-Plaza et al. 2000; Mohanty et al. 2000). Soil water is influenced by topography, soil properties such as texture and vegetation, water routing processes, depth to water table and meteorological conditions (Western and Blöschl 1999; Gómez-Plaza et al. 2001). The complex interaction of these variables can lead to large spatial heterogeneity of soil water and can vary greatly on field as well as point scales (Gómez-Plaza et al. 2000).

Due to the spatial variability of soil water in a field a complete picture requires numerous samples. Fortunately, the knowledge of the mean and variance are sufficient for most practical applications. Randomly taking a few dozen samples is one of the popular methods to obtain the average and variance of soil water. This method is not only time consuming and costly but the random nature precludes the return to the same sample point on consecutive occasions, making it difficult to study long term changes in field water regimes.

Benchmarking of soil water addresses the problems associated with random sampling. A benchmark site is a single reference point that is returned to for successive sampling. This point allows for comparative analysis of changes in soil properties. Traditionally, benchmark sites are selected because a site "looks" representative. This is quite arbitrary and selected sites may deviate from the average behavior of the field. There is a need for identifying benchmark sites that are representative of field average soil water content for agronomic and environmental applications.

Traditional sampling methods assume a random nature to spatial soil water variability, and can only provide estimates of field mean and variance. However, factors controlling soil water exhibit non-random patterns. Spatial patterns in topography, weather, soil, and vegetation within a field or catchment impact water flux patterns giving rise to patterns in soil moisture (Grayson and Western 1998). These patterns of soil moisture may persist over time. To describe these time-persistent spatial patterns, Vachaud et al. (1985) introduced the concept of temporal stability, defined as the temporal invariance in the relationship between spatial location and statistical measure of soil moisture, most often the mean (Grayson and Western 1998). Temporal stability was used as a method of reducing the number of sampling observations needed to characterize a field by Vachaud et al. (1985). An assumption is made that a point in the field

will fall into a statistical rank and will keep that rank for subsequent measurements; therefore, a point that represents the field average will continue to do so over a period of time (Vachaud et al. 1985). Vachaud et al. (1985) reported that temporal stability of soil moisture is realistic because the controlling factors such as soil texture and hydraulic properties affecting soil water are in themselves time stable.

The finding of time stable sites has been reported recently (Grayson and Western 1998; Gómez-Plaza et al. 2000). Grayson and Western (1998) found that spatial patterns of soil water are not persistent for the entire catchment although there were a number of time stable points within the catchment. These were called Catchment Area Soil Moisture Monitoring or CASMM sites. However, CASMM sites were not directly obtained from visual observation of the topography, soil, and vegetation. Gómez-Plaza et al. (2000) found time stable point sources that were in aspect neutral positions within the field. In addition, Gómez-Plaza et al. (2000) found that time stability exists at the transect scale for a bare field, albeit not very strongly. In the same study area the temporal stability broke down when vegetation was introduced as a variable (Gómez-Plaza et al. 2000, 2001). This would indicate that in vegetated areas, myriad soil factors are affecting ground cover and vegetation, thus impacting local control of soil moisture (Gómez-Plaza et al. 2001).

As research has progressed a distinction has been made between wet and dry periods, or preferred states in soil moisture patterns (Kachanoski and de Jong 1988; Grayson et al. 1997; Western and Blöschl 1999). Grayson et al. (1997) classified the controls for different recharge and depletion states as local and non-local. Local controls dominate in dry conditions when evapotranspiration is greater than precipitation. Local controls include the differences in soil properties (i.e. soil texture) and vegetation. Vachaud et al. (1985) were the first to suggest soil texture as a dominant control on time stable water redistribution and soil moisture. Texture becomes important in semi-arid areas with moisture deficits and water redistribution dominated by vertical flow with no connection between adjacent points (Vachaud et al. 1985; Gómez-Plaza et al. 2001). Soil texture is dominant in local control when no vegetation is present and said texture is more determinate in wet periods than in conditions when field evaporation prevails. When there is a moisture surplus, that is, precipitation is greater than evapotranspiration, non-local controls will dominate redistribution (Grayson et al. 1997). These controls are related to upslope topography that includes catchment area, aspect, depth and soil profile curvature (Gómez-Plaza et al. 2001). Western and Blöschl (1999) attributed these differences in local and nonlocal controls to the high degree of organization during wet periods that consist of connected bands of high soil moisture in drainage lines. Moisture in these drainage lines is laterally redistributed by both overland and subsurface flow. However, during dry periods there is limited spatial organization and this spatial variation seems to be mainly random.

There are no definitive criteria for selecting a benchmark site such that it represents the entire field mean and variance. There is conflicting information on what scale temporal stability exists and the factors controlling it. The research to date uses only a single depth for the measurement of soil water content or storage. A comprehensive study is needed to test if the conflicting conclusions are derived from discrepancies in depth measurements. In addition, there are no reports on selecting benchmark sites based on the concept of temporal stability. Therefore, the main objectives of this study are: (1) to identify whether there are time stable sites and if there are, whether time stable sites vary with depth; (2) whether it is possible to identify a time stable

site from the readily measured soil and topographic properties; and (3) to determine if temporally stable sites can be used as benchmark sites.

1.3 Theory

Sufficient observations should be made in the field to determine temporal stability using basic statistics. A spatial pattern can be identified since the location of each observation within the field is known (Vachaud et al. 1985). To find temporally stable benchmark sites Vachaud et al. (1985) calculated the mean relative difference $\delta_t(j)$ and the temporal standard deviation of soil water content $S_t(j)$ (j = location, t = time), at N measured locations.

$$\delta_t(j) = \frac{\Delta_{jt}}{\overline{S}_t} \quad [1.1]$$

where

$$\Delta_{jt} = S_t(j) - \overline{S_t} \quad [1.2]$$

and

$$\overline{S_t} = \frac{1}{N}\sum_{j=1}^{N} S_t(j) \quad [1.3]$$

Similarly, Vachaud et al. (1985) and Gómez-Plaza et al. (2000) used the non-parametric Spearman's test to determine temporal stability. Let R_{ij} be the rank of the variable $S_t(j)$ at location j at time t and $R_{jt'}$ the rank of the identical variable at the same location but at time t'. Spearman's rank is calculated by

$$r_s = 1 - \frac{6\sum_{i=1}^{n}(R_{jt} - R_{jt'})^2}{n(n^2-1)} \quad [1.4]$$

where n is the number of observations. A value of $r_s = 1$ corresponds to identity of rank for any site, or perfect time stability between times t and t'.

1.4 Materials and Methods

The study was carried out in a semi-arid area near Alvena, Saskatchewan, Canada. The site is located 70 km northeast of Saskatoon, on a rolling (slope class 4-3) field. The field is managed under a crop/fallow rotation and was under spring wheat in 2001, and left fallow in 2002, tilled using conventional methods. The field was under Canola in 2003, fallow in 2004, wheat in 2005, and fallow in 2006. Nitrogen is typically applied during seeding at a single rate of 50 kg ha^{-1}. The annual precipitation averages around 350 mm, accumulating mostly as snowmelt in spring and rainfall in summer. With potential evapotranspiration reaching 624 mm per year, water deficits can be as high as 274 mm. It was extremely dry in both 2001 and 2002; the total precipitation for the year 2001 was 159 mm (45% of long term average) while it was the driest year on record for Saskatchewan in 2002. It was very wet in 2004, 2005, and 2006.

A soil survey was carried out in July, 2002. The field was formed on silty Glacio-lacustrine parent material comprised mainly of Orthic Black Chernozems, but also including Orthic

Regosols on the knolls which all belonged to the Blaine Lake association (Acton and Ellis 1978). The soils were classified from cores taken by a truck-mounted hydraulic punch and classified based on the Canadian System of Soil Classification (Soil classification working group 1998). Texture analysis was performed using the simplified hydrometer method (Gee and Bauder 1979). The average texture is that of a silty clay loam with an A horizon averaging 11 cm. A-horizon depth ranges from below 90 cm in the deepest depression to non-existent on the knolls. A summary of clay content, organic carbon and bulk density is provided in Table 1.1.

Table 1.1. Summary of clay content, organic carbon, and bulk density for the studied field.

	Parameter		
	Clay Content	Organic Carbon	Bulk Density
	%	%	$Mg\ m^{-3}$
Mean	29.6	2.2	1.1
Standard Deviation	5.0	0.7	0.1
Minimum	20.4	1.0	0.9
Maximum	41.1	3.8	1.3

A single, 612 m transect running North-South was monitored from April to September in both 2001 and 2002. The transect had 95 capacitance probe tubes spaced at 6 m intervals and was installed to cover several knoll-depression cycles. The tubes for use with a Diviner 2000 were installed to a depth of 160 cm in the spring of 2001. Tubes were installed by removing a 160 cm soil core, of just slightly larger outside diameter than the tubes, using a truck mounted hydraulic punch. Tubes were fitted with a factory supplied installation guide which allowed for installation to full depth without filling the tube with soil. Ten cm of tube was left above ground and the proper receptacle fitting was cemented into place. However, because of the extreme sensitivity of the Diviner 2000, the measurements obtained from the Diviner 2000 were hard to interpret. Therefore, water content measurements were made using the gravimetric method along the transect. The measured data are shown in Figure 1.1.

The mean relative difference and the standard deviation of the daily mean were calculated for the depth of 40 cm. The mean relative difference was then ranked in ascending order and graphed. Points that are sufficiently close to 0 and had small standard deviations given by the error bars were selected from the graph. These potential time stable points were then subjected to a t-test of the mean and points that do not fall within the specified 95% confidence interval were subsequently rejected. The premise is that points will fall into a rank and will retain that rank, or in other words will consistently represent the mean soil moisture as witnessed by the small standard deviation.

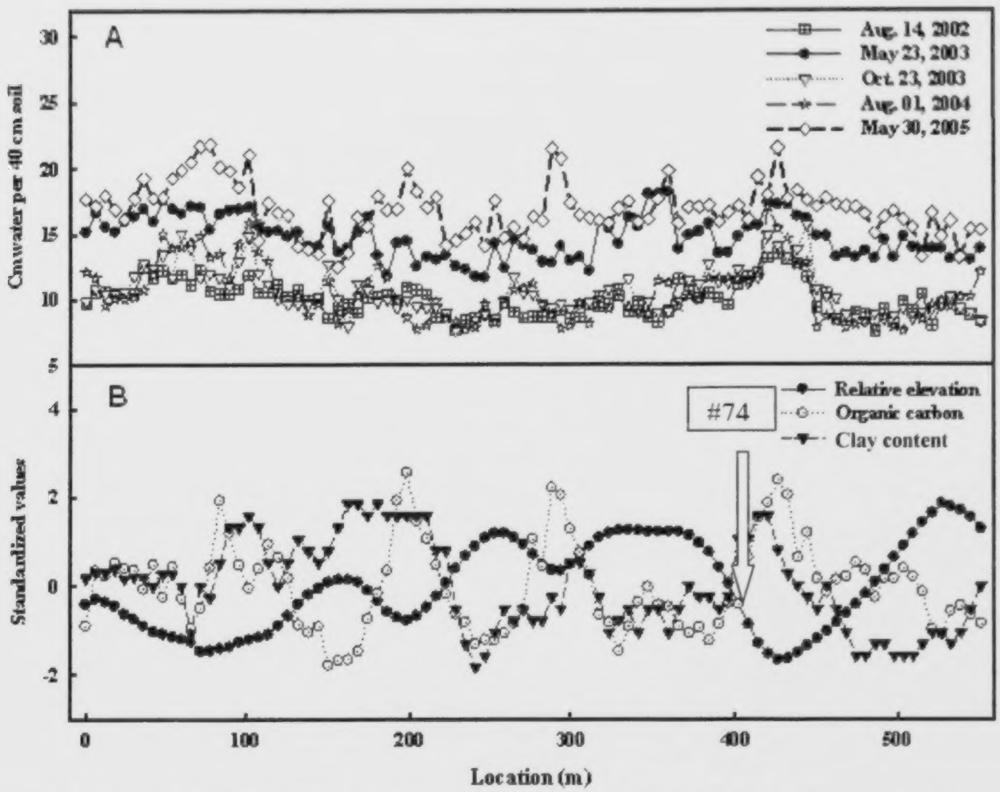

Figure 1.1. Spatial distributions of A) soil water storage during five measurement periods and the distribution of B) clay content, organic carbon, and relative elevation along the study transect at Alvena, SK.

The field was surveyed in May, 2002 using a laser theodolite. Five parallel transects 612 m in length were established running north-south with a lateral distance of 6 m east-west between sample points. Elevation was measured at 6 m intervals along each transect for a total of 512 points in an area of 1.836 ha. This data was then used to produce the topographic information for analysis of results. Three topographic parameters were used to define the wetness index. The curvature was calculated from the elevations using the following approximations (Sinai et al. 1981; Pennock et al. 1994; Shary et al. 2002)

$$M \approx \frac{\partial^2 Z}{\partial X^2} + \frac{\partial^2 Z}{\partial Y^2} = \Delta^2 Z \qquad [1.7]$$

The derivatives in Eq. [1.7] were approximated as

$$\Delta^2 Z = \frac{Z_{i+1,j} + Z_{i-1,j} - 2Z_{i,j}}{\Delta X^2} + \frac{Z_{i,j+1} + Z_{i,j-1} - 2Z_{i,j}}{\Delta Y^2} \qquad [1.8]$$

where Z is elevation, i represents the indices for the x coordinates (along the transect) and j represents the indices for the y coordinates (perpendicular to the transect).

The wetness index of Beven and Kirkby (1979) was calculated as

$$w = \ln\left(\frac{\gamma}{\tan\beta}\right) \qquad [1.9]$$

where γ is the contributing area per unit contour length and $\tan\beta$ is the local slope of the landscape elements.

1.5 Results and Discussion

Examples of spatial and temporal variations of soil moisture storage (40 cm depth) for selected 6 dates (August 14, 2002, Sept. 23, 2002, May 23, 2003, October 23, 2002, August 1, 2004, and May 30, 2005) at each probe location with respect to elevation are presented in Figure 1.1. In spite of the differences in average moisture, the measured soil water content or storage exhibited patterns; soil moisture values in the depression are higher than those on the knolls. Persistent dry conditions tend to homogenize spatial redistribution patterns. Note that to the far right (north) end of the field on the southern aspect, moisture levels in depression area were lower than expected, most likely due to the south facing slope as well as drying winds originating in the south on hot days.

Time-stable sites for soil water storage existed for the studied field. Figure 1.2 shows the standard deviations of mean relative difference (Eq. [1.3]) for soil water storage at different depths. Sites that are close to the mean with corresponding small standard deviations were selected as time-stable sites, according to Vachaud et al. (1985). A standard two-tailed t-test about the mean was then performed on the chosen sites. Sites that have a mean significantly different from zero are rejected as time stable sites at a 95% confidence interval. The site that was chosen as a representative benchmark site was location # 74, which was on the midslope position. Figure 1.1 contains a vertically exaggerated longitudinal profile that shows site 74 occurring in a slope-neutral position in the field.

Table 1.1 Mean and standard deviation of soil water storage at the Alvena site during five observation periods and relationships to relative elevations (RE), organic carbon (OC), and clay content (CL).

	Mean (cm per 40 cm soil)	R^2 (n = 104)		
		RE	OC	CL
Aug.14, 2002	10.07 (1.32)†	0.39*	0.06	0.22*
May 23, 2003	14.71 (2.15)	0.18*	0.03	0.06
Oct. 23, 2003	10.67 (1.79)	0.26*	0.05	0.08
Aug. 01, 2004	10.52 (1.18)	0.29*	0.03	0.14*
May 30, 2005	17.09 (2.45)	0.23*	0.01	0.02

*Significant at P = 0.01, †Standard deviation

Temporal persistence of spatial patterns was examined for selected days using the Spearman's rank correlation (Table 1.2). The results show a good correlation with a high correlation coefficient of 0.64 between soil water storage measured on August 1, 2004 and May 30, 2005 and a low correlation coefficient of -0.03 between water storage measured on Sept. 14, 2002 and May 30, 2005. Contrast to Vachaud et al (1985) and Kachanoski and de Jong (1988), persistent patterns existed between some of the dates, but not for all the dates.

Table 1.2. Spearman's rank correlations illustrating persistence of spatial patterns.

Day	8/14/02	9/14/02	5/23/03	10/23/03	8/1/04	5/30/05
8/14/02	1	0.47	0.49	0.19	0.13	0.10
9/14/02		1	0.38	0.22	0.29	-0.03
5/23/03			1	0.21	0.20	0.05
10/23/03				1	0.64	0.29
8/1/04					1	0.32
5/30/05						1

The finding of temporally stable sites is supported by others (Vachaud et al. 1985; Kachanoski and de Jong 1988; Grayson and Western 1998; Gómez-Plaza et al. 2000). Within the same field, time-stable sites can be different for various depths. For this study, point source time stable sites were located, while overall spatial patterns did not display consistent patterns. This is similar to Grayson and Western (1998) who found that transect scale temporal stability did not exist while point scale temporal stability exists because there was no spatial pattern that could be shown.

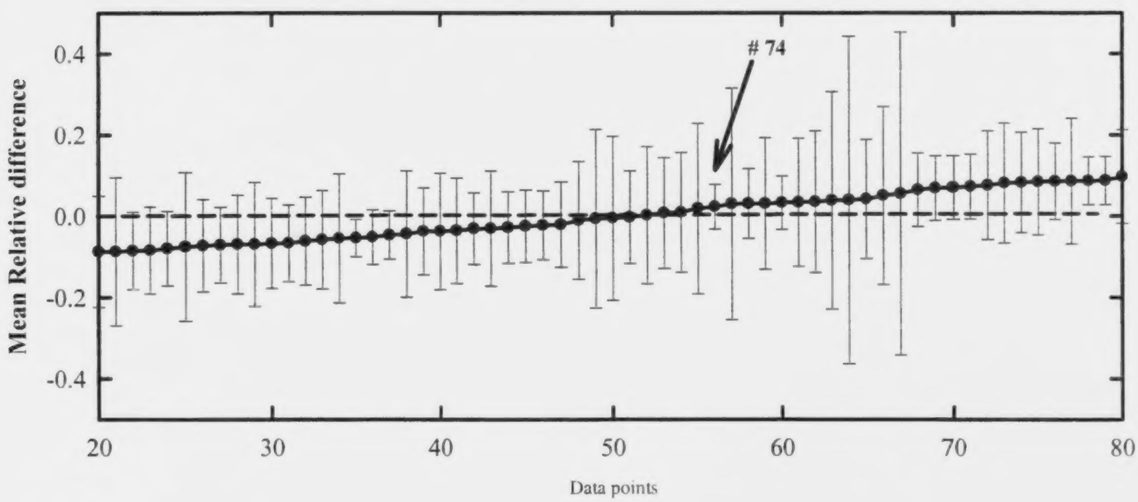

Figure 1.2. Mean relative differences and standard deviations for different sampling locations ranked according to mean relative differences.

Temporal persistence of spatial patterns was examined for selected days using the Spearman's rank correlation (Table 1.2). The results show a good correlation with a high correlation coefficient of 0.64 between soil water storage measured on August 1, 2004 and May 30, 2005 and a low correlation coefficient of -0.03 between water storage measured on Sept. 14, 2002 and May 30, 2005. In contrast to Vachaud et al. (1985) and Kachanoski and de Jong (1988), persistent patterns existed between some of the dates, but not for all the dates.

1.6 Conclusions

A representative soil water benchmark site has the potential to provide important information for environmental monitoring. Temporally stable spatial patterns within the field led to the determination of benchmark sites for various depths that were representative of field mean soil moisture. Time stable sites showed poor relationships to soil and topographic properties suggesting the absence of a single dominant control. The most consistent control was catchment area, a non-local control indirectly affecting evaporative losses. Future studies should look at the effect of controls on all depths in an effort to determine time stable sites *a priori* as well as upscaling of point source temporal stability. Benchmark sites whether they represent mean or extreme values can greatly improve sampling efficiency and can provide useful information for environmental monitoring.

1.7 References

Acton, D.F. and J.G. Ellis. 1978. The soils of the Saskatoon map area, 73-B, Saskatchewan. Sask. Institute of Pedology Publ. 54.

Beven, K.J. and M.J. Kirkby. 1979. A physically-based, variable contributed area model of basin hydrology. Hydrol. Sci. Bull. 24:43-69

Gee, G.W. and J.W. Bauder. 1979. Particle size analysis by hydrometer: a simplified method for routine textural analysis and a sensitivity test of measurement parameters. Soil Sci. Soc. Am. J. 43:1004-1007.

Gómez-Plaza, A., M. Martinez-Mena, J. Albaladejo, and V.M. Castillo. 2001. Factors regulating spatial distribution of soil water content in small semi-arid catchments. J. Hydrol. 253(1-4):1261-1277.

Gómez-Plaza, A., J. Alvarez-Rogel, J. Albaladejo and V.M. Castillo. 2000. Spatial patterns and temporal stability of soil moisture across a range of scales in a semi-arid environment. Hydrol. Processes. 14(7):1261-1277.

Grayson, R.B., and A.W. Western. 1998. Towards areal estimation of soil water content from point measurements: time and space stability of mean response. J. Hydrol. 207(1-2):68-82.

Grayson, R.B., A.W. Western, F.H.S. Chiew, and G. Blöschl. 1997. Preferred states in spatial soil moisture patterns: local and non-local controls. Water Resour. Res. 33(12): 2897-2908.

Kachanoski, R.G., and E. de Jong. 1988. Scale dependence and the temporal persistence of spatial patterns of soil water storage. Water Resour. Res. 24 (1):85-91

Mohanty, B.P., J.S. Famiglietti, and T.H. Skaggs. Dec. 2000. Evolution of soil moisture spatial structure in a mixed vegetation pixel during the Southern Great Plains 1997 (SGP97) Hydrology Experiment. Water Resour. Res. 36(12):3675-3686.

Paltineanu, I.C. and J.L. Starr. 1997. Real-time soil water dynamics using multisensor capacitance probes: laboratory calibration. Soil Sci. Soc. Am. J. 61:1576-1585.

Pennock, D.J., F.L. Walley, M. Solohub, B.C. Si, and G.L. Hnatowich. 2001. Topographically controlled yield response of Canola to nitrogen fertilizer. Soil Sci. Soc. Am. J. 65:1838-1845.

Pennock, D.J., D.W. Anderson and E. de Jong. 1994. Landscape-scale changes in indicators of soil quality due to cultivation in Saskatchewan, Canada. Geoderma. 64:1-19.
Shary, P.A., L.S. Sharay, and A.V. Mitusov. 2002. Fundamental quantitative methods of land surface analysis. Geoderma. 107:1-32
Si, B.C. and R.E. Farrell. 2003. Scale-dependant relationship between wheat yield and topographic indices: A Wavelet approach. Submitted to Soil Sci. Soc. Am. J. on Jan 22, 2003.
Sinai G., D. Zaslavsky and P. Golany. 1981. The effect of soil surface curvature on moisture and yield – Beer Sheba observation. Soil Sci. 132:367-375.
Soil classification working group. 1998. The Canadian system of soil classification. Agric and Agri-Food Can. Publ. 1646 (Revised). 187pp.
Vachaud, G., A. Passerat De Silans, P. Balabanis, and M. Vauclin. 1985. Temporal stability of spatially measured soil water probability density function. Soil Sci. Soc. Am. J. 49:822-828.
Western, A.W., and G. Blöschl. 1999. On the spatial scaling of soil moisture. J.Hydrol. 217:203-224.

Study II. Selection of soil fertility benchmark site in a landscape of south-central Saskatchewan

2.1 Summary

Soil water and nutrient availability are major limiting factors for crop production in the Canadian prairies. Most variations in soil properties observed across prairie farm fields are the result of the effect of landscape on water and soil redistribution. The relationships among soil chemical properties (pH, electrical conductivity, organic matter and available nutrients), soil water, elevation and canola seed yield were investigated in a transect across a hummocky, undulating farm field in the Brown soil zone of south-central Saskatchewan. Overall, seed yield was highest in foot slope positions in the landscape where soil organic matter, nutrients and available water content were higher. Correlations between soil properties and seed yield were highest for pH ($R= -0.46$, $p < 0.01$), which was followed by organic C % ($R= 0.27$, $p < 0.05$), water content ($R=0.23$), extractable K ($R=0.18$) and N and P supply rates to exchange resin membranes ($R=0.15$). Extractable N and P were poorly correlated with seed yield ($R<0.1$). The landscape region with soil parameters and yield closest to the average for the entire transect was the back slope region, suggesting that in similar landscapes, this region would be most appropriate for selection as a representative benchmark sampling site.

2.2 Introduction

Soil water and nutrient availability are major limiting factors for crop production in the semi-arid to sub-humid region of the Canadian prairies. The soils are formed on glacially derived parent material deposited about 12000 years ago (Christiansen 1979). Glacial till deposits typically provide a hummocky, undulating topography. Most variation in soil properties observed in undulating glacial till landscapes is the result of the effect of landscape on water and soil distribution. Run-off of rainwater and snowmelt from upslope regions to depressions carries topsoil and alters the distribution of water and nutrients. The level of nutrients along a catena follows a similar trend to that of the soil movement (Stevenson et al. 1996; Jowkin and Schoenau 1998). Pennock et al. (1987) used gradient,

plan curvature, and profile curvature to identify landform elements and the flow of water in relation to topographic variation in prairie landscapes.

Topography is the fundamental control of soil genesis in semi-arid and sub-humid climatic conditions (Anderson 1987). The distribution of moisture in a semi-arid landscape affects soil development, microbial activity, crop growth and hence soil organic matter and nutrient accumulation. Water transports solutes and suspended particles within and out of the landscape by overland flow, through flow or lateral flow (Richardson et al. 1992). Water also moves vertically downwards, carrying soluble materials. Therefore a net loss of solutes occurs at the surface and in upslope regions compared to locations deeper in the profile and down slope. Moisture content, organic matter and soil nutrients are increased from upper slope, to mid slope, to foot slope positions. This strongly influences fertility and crop growth potential, with greater productivity generally associated with lower slope positions (Verity and Anderson 1990; Moulin et al. 1994).

Areas of low elevation (for example foot slopes and toe slopes) may be at or near saturation due to the influence of water table and these foot slope areas may also be influenced by salinity due to capillary rise (Anderson 1987). Upper slope positions are rarely influenced by the water table, where significant local relief is present. In upper slope positions, water moves soluble salts to depth (2-4m) and then possibility to the ground water table, although recharge rates are low. Saline and sodic soils usually occur in areas where ground water moves upward from a shallow water table close to the soil surface. The water carries salts, and these salts accumulate at or near the soil surface as the water evaporates. Zones surrounding foot slopes with high water tables may be discharge areas associated with salinity.

Steeply sloping, erosional areas where run off occurs have lower moisture, poorer soil structure and lower nutrient levels. Available nitrogen (N) and phosphorus (P) are reported to be reduced at the shoulder and increase progressively down slope where deposition is occurring (Malo and Worcester 1975). Overall, the nature of water flow as related to elevation and surface curvature in soil landscapes has a strong influence on nutrient availability, organic matter and crop production.

The variability inherent in such landscapes creates difficulty in selecting a benchmark site for sampling that is representative of "average" conditions across the landscape. Knowledge of which landform element or landscape position has soil properties closest to the average of the entire landscape would facilitate selecting the best benchmark sites for soil water and fertility assessment for fertilizer recommendations. Furthermore, knowing which soil properties are most closely related to yield in such landscapes is useful in making decisions about which soil properties would be best to measure.

The objective of the research reported on in this paper was 1) to determine how chemical and physical soil properties measured along a transect are related to canola seed yield and 2) identify the landform elements or regions that have soil and crop properties closest to the average of the entire landscape. This was accomplished by measuring soil properties and crop yield at 41 points located in a transect across a typical hummocky farm field in south-central Saskatchewan, Canada.

2.3 Materials And Methods

2.3.1 Study Site

The site was a 35 ha farm field (legal location: NE 25, Township 20, Range 4, W of 3) located about 150 km south of Saskatoon, Saskatchewan, Canada. In the spring of 2005, a transect of 280 m length was laid out in an east-west direction across the field. The soil in the field is classified and mapped as Ardill-Kettlehut association: a Brown Chernozem of dominantly Rego and Orthic series in upper and mid slopes with significant Gleysolic soils in depressions. Saline-solonetzic areas sometimes occur at toe slopes. The topography is classified as hummocky or knob and kettle, typical of glacial till and with loam-clay loam texture. Points 7 m apart were selected along the transect and soil samples were collected on May 9, 2005 using a hydraulic punch truck. On May 9, 2005 the field was seeded to canola quality mustard (*Brassica juncea* cv Dahinda). At the same transect locations, square meter samples of canola were harvested on August 16, 2005.

The points along the transect were divided into five groups of landform elements according to elevation, plan and surface curvature: divergent shoulders (DS), convergent shoulders (CS), back slopes (B), convergent foot slopes (CF) and flat foot slope (FF) regions (Figure 2.1; Table 2.1). The DS and CS points had positive or negative slopes less than 2%. The CF points were located at the base of the back slopes (B), where run off from the adjacent slopes accumulated and suspended sediments would settle out. The flat foot slope (FF) represents a basal or transitional area in the landscape. A cross sectional view of the transect showing the relative elevation, location of the sampling points and the five groups of landform elements is provided at the top of Figure 2.1.

Table 2.1. Landform element classification with soil parameters and grain yield at each one of the forty-one sample location points along the transect, 2005.

Sample Location Point	Landscape region	Relative elevation (m)	Soil water content (%)	Soil PO_4-P supply rate ($\mu g/cm^2$)	Soil NO_3-N supply rate ($\mu g/cm^2$)	Soil extract NH_4-N ($\mu g/g$)	Soil extract NO_3-N ($\mu g/g$)	Soil extract P ($\mu g/g$)	Soil extract K ($\mu g/g$)	pH	EC (mS/cm)	Organic C %	Seed yield kg/ha
1	conv.footslope	-0.77	32.5	0.29	23.3	2.4	11.0	10.9	273	7.51	0.23	1.11	1586
2	conv.footslope	-0.65	48.8	0.32	17.4	2.9	9.2	8.5	268	7.76	0.24	1.29	1722
3	back slope	0.05	35.0	1.01	14.8	1.4	13.2	8.1	259	7.77	0.34	0.96	1261
4	back slope	0.47	41.5	1.94	17.2	0.9	11.6	12.3	328	7.51	0.21	1.27	1404
5	back slope	0.87	40.0	1.82	9.8	0.6	6.4	8.8	190	7.45	0.14	1.15	1580
6	back slope	1.14	32.2	1.56	15.4	0.4	10.8	8.9	134	7.49	0.21	1.00	1200
7	div. shoulder	1.28	35.1	2.24	22.2	0.7	11.2	8.2	135	7.64	0.17	1.14	1831
8	div. shoulder	1.25	29.0	0.40	9.9	1.4	6.7	3.4	198	7.69	0.19	0.87	1662
9	div. shoulder	1.18	28.8	0.30	11.5	3.2	9.6	5.1	196	7.74	0.22	0.90	1764
10	div. shoulder	1.07	30.4	0.16	6.5	3.7	4.4	4.8	158	7.94	0.18	0.67	1388
11	back slope	1.07	30.4	0.16	6.5	3.7	4.4	4.8	158	7.94	0.18	0.67	1388
12	back slope	0.82	40.1	0.82	8.6	5.2	7.3	9.4	207	7.94	0.24	1.05	1341
13	back slope	0.60	43.8	0.00	9.0	5.5	6.5	11.3	182	7.82	0.78	1.00	1725
14	conv.footslope	0.28	29.0	0.29	5.9	4.5	7.3	5.9	147	7.90	0.22	0.74	1393
15	conv.footslope	0.08	35.1	1.27	9.3	6.0	6.4	9.4	139	7.73	0.18	0.67	1044
16	flat footsope	-0.07	40.8	0.00	10.1	4.8	7.3	6.8	162	7.88	0.20	0.50	1324
17	flat footslope	-0.08	36.7	0.57	6.3	8.1	6.0	5.5	190	7.42	0.20	0.76	1562

18	flat footslope	-0.12	31.8	0.45	8.3	3.9	9.7	10.3	245	7.47	0.19	1.02	1200
19	flat footslope	-0.06	28.4	0.94	12.3	1.4	8.8	5.8	125	6.89	0.13	0.81	1639
20	flat footslope	-0.02	34.7	1.26	7.1	7.2	8.1	8.4	291	6.65	0.14	0.96	1528
21	flat footslope	0.00	39.5	1.39	10.6	1.0	6.2	8.5	270	6.85	0.17	1.07	1661
22	flat footslope	0.09	45.4	1.68	12.4	2.9	8.2	14.4	384	6.77	0.19	1.18	2052
23	flat footslope	0.09	44.0	1.81	5.4	2.5	6.5	9.5	457	7.02	0.17	1.25	1481
24	flat footslope	0.16	41.6	0.61	10.2	4.1	8.9	6.2	310	6.37	0.12	1.15	2578
25	flat footslope	0.24	45.7	1.37	16.1	2.5	11.1	9.4	347	5.98	0.13	1.28	1734
26	flat footslope	0.26	39.3	1.63	7.2	3.3	6.5	9.6	394	6.22	0.11	1.05	1572
27	conv.footslope	0.42	44.0	1.71	16.6	2.7	11.9	12.1	222	7.10	0.54	0.81	1646
28	conv.footslope	0.44	49.4	1.01	10.0	3.9	8.6	12.1	235	7.16	1.11	0.88	1760
29	back slope	0.71	42.0	0.55	7.2	4.0	4.4	4.8	280	7.41	0.19	0.83	1600
30	back slope	1.12	35.2	1.25	6.3	3.5	5.4	6.6	306	6.88	0.12	0.83	2016
31	back slope	1.36	39.2	2.14	16.0	7.5	10.0	11.3	258	6.41	0.16	1.45	1758
32	back slope	1.55	37.4	1.36	12.0	3.7	8.7	7.9	147	6.56	0.24	1.00	2842
33	div. shoulder	1.59	29.5	1.09	8.4	7.0	5.8	7.3	114	6.51	0.11	0.85	1672
34	div. shoulder	1.73	32.8	0.61	6.1	2.9	3.6	4.3	102	6.80	0.13	0.84	1094
35	onv.shoulder	1.71	30.7	0.07	13.7	3.2	7.9	3.2	68	7.07	0.14	0.66	1570
36	conv.shoulder	1.65	30.8	0.22	8.3	1.3	6.9	3.9	88	7.39	0.18	0.82	1012
37	conv.shoulder	1.44	35.8	0.69	16.5	3.6	13.6	7.2	165	7.45	0.21	1.07	1663
38	conv.shoulder	1.50	44.6	0.46	8.1	4.2	9.8	10.1	168	7.60	0.23	0.93	1305
39	conv.shoulder	1.56	33.0	0.06	10.0	2.8	7.5	3.1	111	7.47	0.17	0.89	1843
40	conv.shoulder	1.62	35.8	0.62	9.8	1.8	6.7	4.1	119	7.11	0.12	0.84	2006
41	conv.shoulder	1.68	36.5	0.27	8.1	2.7	7.8	6.8	142	7.44	0.15	0.63	1617

2.3.2 Soil Sampling and Analysis

Soil samples were taken from three depths (0-10, 10-20, and 20-30 cm) at each of the forty one points. The distance between consecutive points was 7 m. Following collection, the soil samples were air-dried at room temperature. The samples were then ground to pass through a 2 mm sieve. These samples were used to determine pH, electrical conductivity (EC), ammonium-N (NH_4-N), nitrate-N (NO_3-N), P, K and organic C. At the same time as the samples were collected for soil chemical properties, soil samples were taken from five depths (0-10,10-20, 20-30, 30-40, and 40-50 cm) at each point and these samples were used directly to determine soil gravimetric water content (W/W basis). The average of the water contents for the six depth increments is reported.

The pH of the soil samples was measured on a 2:1 water : soil extract (Hendershot et al. 1993) using a Beckman 50 pH meter and EC was measured on the same extracts using a Horiba Es-12 conductivity meter. Total organic carbon was measured by automated combustion using a LECO carbon analyzer.

Extractable, available NH_4-N and NO_3-N concentrations were determined using 2 M KCl extraction (Keeney and Nelson 1982) while extractable K and P were determined by extraction with modified Kelowna extracting solution (Qian et al. 1994). The NH_4-N, NO_3-N and P in the filtered extracts were measured by Technicon automated colorimetry while K was measured by

flame emission spectroscopy. The supply rate or flux of plant available NO_3-N and phosphate-P (PO_4-P) was measured in the soil by ion exchange resin membranes (Qian and Schoenau 2002). In this method, a small sheet of anion exchange membrane (Western Ag Innovations, Saskatoon, SK, Canada) in bicarbonate form was placed in direct contact with moist soil in a 40 dram vial for a 24 h period. The nitrate and phosphate ions that exchanged with counter ions on the membrane and became sorbed over the 24 h period were then eluted from the resin with 0.5 M HCl and measured colorimetrically.

2.3.3 Crop Sampling

The square meter samples of canola collected from each point on the transect were first dried at 35°C for 48 h. Then the seed was separated from the straw using a mechanical thresher. Seed and straw weights were recorded separately.

2.3.4 Data Analysis

Relationships between soil and plant parameters were evaluated by linear regression and determination of correlation coefficient (R) using the Excel software program. In order to determine the closest transect element to the transect average for the measured variables, first the average value for each of the variables for the points within a landform grouping was calculated. Then, a general average for each measured variable along the transect was calculated using the data obtained for the forty one points. The average value for each landform element group was then subtracted from the general average and the landform element with the least difference from the transect average identified.

To find the landscape elements that best represent the field average in all soil properties and crop yield, we calculated the mean relative difference $\delta_t(j)$ and the temporal standard deviation of $S_t(j)$ (j = landscape element, t = soil property) at N landscape elements (for this case, N = 5) according to Vachaud et al. (1985) and Tallon and Si (2004).

$$\delta_t(j) = \frac{\Delta_{jt}}{\overline{S}_t} \qquad [2.1]$$

where

$$\Delta_{jt} = S_t(j) - \overline{S_t} \qquad [2.2]$$

and

$$\overline{S_t} = \frac{1}{N}\sum_{i=1}^{M} S_t(i) \qquad [2.3]$$

where M is the number of observations for a soil property or crop yield (M=40 for this study).

The landscape element with the smallest standard deviation of $\delta_i\ (j)$ indicates that the landscape element has the smallest overall deviation from the overall mean value for all the soil properties (population means).

2.4 Results and Discussion

2.4.1 Relationship Between Soil Properties, Elevation, and Seed Yield Soil Moisture and Organic C

The major factor limiting plant growth on the prairies is soil moisture. The accumulation of organic matter at the soil surface is related to the inherent soil fertility, microclimate and availability of water for crop growth. Whitman et al. (1985) observed that the effect of gradient and aspect on incoming radiation strongly influenced crop growth. Plant nutrients and cation exchange capacity often increase down a slope (Malo and Worcester 1975; Gregorich and Anderson 1985) and plant growth and organic matter accumulation should be greatest where the water content is high due to a concave surface form (Sinai et al. 1981). The equilibrium level of organic matter in soil depends on the relative rates of addition and decomposition, and is affected by the composition of plant residues, moisture, temperature and aeration.

Along the transect, areas of high elevation were generally associated with low soil water content and low seed yield (Fig. 2.1). Soil water content tended to decrease with increase in relative elevation. Hanna et al. (1982) observed that low slope positions contained on average 5 cm more available moisture than upper slope positions in the spring of the year. The correlation value between water content and relative elevation was R= -0.34 in the current study and is significant at $p < 0.01$. A similar pattern was observed for soil organic C content (Fig. 2.1). Across the entire transect, however, relative elevation was not significantly correlated with seed yield (R=0.08).

Table 2.2. Average values of soil parameters and seed yield in the five landform element groupings along the transect for 2005.

Region	Soil water content (%)	Soil P supply rate ($\mu g/cm^2$)	Soil NO_3-N supply rate ($\mu g/cm^2$)	Soil extract NH_4-N ($\mu g/g$)	Soil extract NO_3-N ($\mu g/g$)	Soil extract P ($\mu g/g$)	Soil extract K ($\mu g/g$)	pH	E.C. (mS/cm)	Organic. C (%)	Seed yield (kg/ha)
DS	30.90	0.80	10.80	3.10	6.90	5.50	150.50	7.39	0.17	0.88	1568
CS	35.30	0.34	10.60	2.80	8.60	5.50	122.90	7.36	0.17	0.83	1574
B	37.90	1.15	11.20	3.30	8.10	8.60	222.60	7.38	0.26	1.02	1647
CF	39.80	0.82	13.70	3.70	9.10	9.80	214.00	7.53	0.42	0.92	1486
FF	38.90	1.07	9.60	3.80	7.90	8.60	288.60	6.87	0.16	1.00	1667
Whole transect	36.60	0.83	11.20	3.40	8.10	7.60	199.70	7.30	0.24	0.93	1588

The amount of organic matter tended to decrease with increase in relative elevation, partly due to processes of tillage and water erosion from uplands and sedimentation in depressions, along with greater moisture for plant production in lower elevation regions. In the five groupings of sampling points into landform element classes along the transect, water content followed the

relationship: CF $\geq$ FF > B > CS >DS according to Table 2.2. Higher soil water in foot slope regions of the landscape is expected due to run off and accumulation. However, seed yield in the five regions showed the following pattern: FF $\geq$ B > CS > DS > CF. Relationships between yield and topography can be complex and variable from year to year (McConkey et al. 1996), as accumulation of water in foot slopes may enhance yield in drier years but depress yield due to flooding in wet years.

The pattern in organic C was B $\geq$ FF >CF >DS >CS . Higher water in CF but low yield and organic matter could reflect influence of high water table and salt accumulation on lowering plant production in the CF region of this landscape. The correlation values for different soil parameters with yield and elevation are given in Table 2.3.

Table 2.3. The correlation coefficients for relationships between canola seed yield, elevation and soil properties across the transect for 2005.

	Water content	Organic C	Extractable NO_3^--N	NO_3-N Supply Rate	Extractable P	P Supply Rate	Extractable K	EC	pH
Seed Yield	0.23	0.27	0.09	0.16	0.02	0.15	0.18	0.03	-0.46
Elevation	-0.34	-0.24	-0.18	-0.17	-0.45	-0.09	-0.58	-0.14	-0.02

2.4.2 Available Nutrients for 2005

Weathering intensity is a major factor affecting the transformation and distribution of soil phosphorus. Higher levels of organic P reported in foot slope positions of catenas are due to increased organic matter, biological activity and weathering related to increased moisture levels (Roberts et al. 1985). Lower levels of available P in upslope regions were reported to be due to erosion on the shoulder slopes (Malo and Worcester 1975). The available soil P supply rate tended to be lowest in shoulder regions (Fig. 2.1). However, soil P supply was not strongly related to elevation while extractable P was more closely related to elevation (Fig. 2.2). Across the landscape, the relationship between seed yield and extractable P, and P-supply rate to resin were not significant at $p < 0.05$.

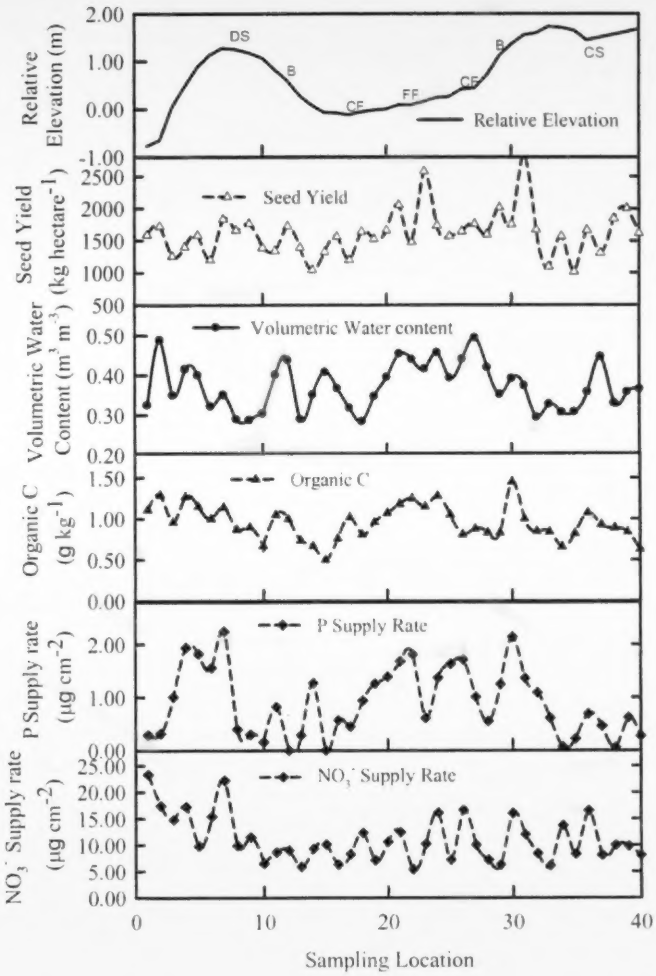

Figure 2.1. Elevation, seed yield, water content, organic carbon and phosphate and nitrate supply rates across the transect for 2005.

Mineralization processes transform N in soil organic matter to the plant-available ammonium form. Mineralization increases with temperature and is enhanced by adequate, although not excessive, soil moisture and a good supply of oxygen (Ellert and Bettany 1992). Ammonium is relatively immobile as it is strongly adsorbed to clay minerals and organic material, but may be moved in surface water via attachment to sediment that is suspended in water. It is readily converted into nitrate by nitrification process. As total soil N concentration increases, the quantity of nitrogen mineralized increases and contributes to increased plant available N. Low soil organic matter contents and dry conditions were associated with reduced mineralization in

shoulder positions of Saskatchewan landscapes (Qian and Schoenau 1995). The results of the current study (Figs. 2.1 and 2.2) also show that inorganic N supply rates and concentrations in shoulder positions are low relative to foot slope positions.

In the convergent foot slope and flat foot slope position (around sampling location points 20 to 30) extractable NO_3-N and NH_4-N were higher than in shoulder positions. In these areas, mineralization and nitrification rates would be higher due to higher water content and organic matter (Fiez et al. 1994). Across the landscape, the supply rate of NO_3-N was better correlated with yield than extractable NO_3-N, possibly because the supply rate measurement for 24 h includes a component of mineralization and N supply power (Qian and Schoenau 2005).

Soil moisture can have effects on extractable, available K by affecting rate of mineral weathering and transport of K. In sandy soils, K leaching losses may be high while in fine textured soils that adsorb and fix K, losses are small (Bertsch and Thomas 1985). Potassium availability in the surface horizons is greater than sub-surface horizons due to greater weathering of the clay minerals to release available K near the soil surface. Extractable K levels in the five landscape element groups followed the general pattern of FF > B > CF > DS > CS.

Across the landscape, extractable K was strongly and inversely related to elevation ($R= -0.58$, $p < 0.01$) with amounts of extractable K in shoulder positions lower than in foot slope positions (Fig. 2.2). In the shoulders, soil is higher in sand content compared to the foot slope positions (data not shown) where eroded clay minerals accumulate. In depressions where moisture content is high, the K absorbed by crop roots also increases. The correlation between extractable K and seed yield ($R=0.18$) was similar to that observed for soil nitrate and phosphate supply rates.

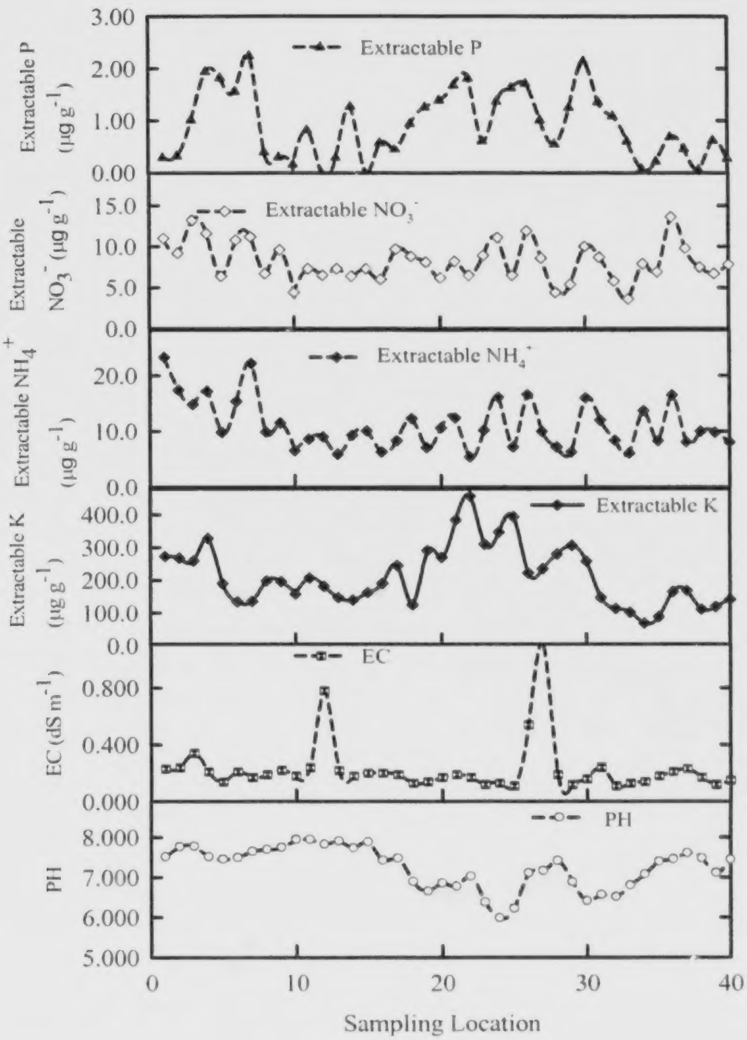

Figure 2.2. Extractable nutrient concentrations, electrical conductivity and pH across the transect.

Across the landscape, extractable K was strongly and inversely related to elevation ($R = -0.58$, $p < 0.01$) with amounts of extractable K in shoulder positions lower than in foot slope positions (Fig. 2.2). In the shoulders, soil is higher in sand content compared to the foot slope positions (data not shown) where eroded clay minerals accumulate. In depressions where moisture content

is high, the K absorbed by crop roots also increases. The correlation between extractable K and seed yield (R=0.18) was similar to that observed for soil nitrate and phosphate supply rates.

2.4.3 Salinity and pH for 2005

Increase in salinity in the lower slope positions of some landscapes has been reported to occur as saline water moves from saturated soil in upper positions down slope, and then to the surface by capillary rise, leaving behind salts by subsequent evaporation (Sandovel et al. 1961). The presence of a high water table will have a strong influence on soil moisture dynamics in the landscape. Areas of low elevation (for example foot slope and toe slope) may be at or near saturation due to the influence of a high water table and capillary rise. The results of this study agree with this general trend. Field soil salinity is not elevated, except near points 12 and 27 (Fig 2.2). Evidence of increased soil salt concentration occurs likely because of movement of saline water from upper slopes to these areas, where water evaporates and sulfate salts are deposited, causing soil salinity (Schoenau and Germida 1992). Salinity occurs due to upward movement of ground water from a shallow water table close to the soil surface. Evidence for this is found in the high soil water contents at sampling location points 12 and 27 (Fig. 2.1). As water evaporates, sulfate salts are deposited in this position. Overall, salinity is not a strong controlling factor on yield in this landscape as the correlation between EC and grain yield was low (R=0.03) across the landscape.

The pH of the shoulder regions (DS and CS) was usually higher than foot slopes (Fig. 2.2), likely due to past erosion removing topsoil and exposing carbonate-rich sub-soils. Nitrification and leaching of NO_3-N can cause a net acidification. Generally, pH values close to 7 were associated with the highest yields. Across the landscape the correlation between pH and seed yield was inverse (R= -0.46, $p < 0.01$) and the relation between pH and yield was the strongest of the soil parameters measured. The pH likely integrates and reflects a number of functions controlling yield in this landscape including organic matter content, nutrient availability, carbonate content and overall topsoil thickness.

2.4.4 Identification of Landform Element Most Representative of Entire Landscape for 2005.

The convergent regions and the back slope have soil properties that are closest to the average of the properties across the entire transect (Tables 2.4 and 2.5). In particular, the back slope had the largest number of soil properties closest to the average for this transect, as indicated by the lowest standard deviation (Table 2.5). This suggests that in similar fields, back slope regions would be most suitable as a benchmark for measurement of soil and crop characteristics intended to represent as best as possible the entire field.

2.4.5 Benchmark Selection for 2006

The transect benchmark was chosen based on the criteria set out in the research design. The landscape element whose average of each variable was closest to the transect average was denoted the "benchmark". As the flat foot slopes had the greatest number of properties closest to the average, this landscape element may be considered to be the best benchmark (Table 2.6). The FF region of the transect had the most variable averages closest to the transect averages. Measurement variables such as nitrate, that were well correlated with yield also showed least deviation from the average for this landscape element. However, if stored spring water is considered to be most important, then shoulder positions might be best. It is at shoulder positions where water limitations would be expressed to the greatest extent.

Table 2.4. Deviation of average value for each landform element region from the average value for the entire transect (landscape).

Region	Soil water content	Soil P supply rate	Soil NO_3-N supply rate	Soil extract NH_4-N	Soil extract NO_3-N	Soil extract P	Soil extract K	pH	E.C.	Organic C	Seed yield
DS	-6.1	-0.03	-0.41	-0.22	-1.23	-2.08	-49.19	0.08	-0.07	-0.05	-20
CS	-3.0	-0.49	-0.55	-0.55	0.48	-2.11	-76.83	0.06	-0.06	-0.10	-15
B*	0.9	0.31	-0.03	-0.04	-0.04	0.97	22.88	0.08	0.02	0.09	59
CF	2.9	-0.02	2.55	0.37	0.97	2.23	14.27	0.22	0.19	-0.01	-103
FF	2.1	-0.03	-0.41	-0.22	-1.23	1.00	88.88	-0.44	-0.08	0.07	78

* Closest to the average value for the entire landscape.

Table 2.5. Relative deviation of average value for each landform element region from the average value for the entire transect (landscape).

Region	Soil water content	Soil P supply rate	Soil NO_3-N supply rate	Soil extract NH_4-N	Soil extract NO_3-N	Soil extract P	Soil extract K	pH	E.C.	Organic C	Seed Yield	SD
DS	-0.16	-0.03	-0.04	-0.06	-0.15	-0.26	-0.23	0.01	-0.30	-0.05	-0.01	**0.11**
CS	-0.08	-0.54	-0.05	-0.16	0.06	-0.26	-0.35	0.01	-0.26	-0.10	-0.01	**0.18**
B*	0.02	0.34	0.00	-0.01	0.00	0.12	0.11	0.01	0.09	0.09	0.04	**0.10**
CF	0.08	-0.02	0.23	0.11	0.12	0.28	0.07	0.03	0.82	-0.01	-0.06	**0.24**
FF	0.06	-0.03	-0.04	-0.06	-0.15	0.13	0.41	-0.06	-0.34	0.07	0.05	**0.19**

* Closest to the average value for the entire landscape.

On undulating topography, soil forming factors and erosion do not act uniformly, but vary with landscape position (Brydon 1986). This inconsistency is why benchmark selection is so important. The analyzing of an entire landscape requires extensive efforts, but if one or two benchmarks were chosen, analysis would become much more convenient and efficient.

2.4.6 Reselection of Benchmark for 2006

The benchmark selection in this study was based on all variables analyzed. These variables, however, did not all have the same effects on canola yield. Soil water content, phosphorus and nitrate were all directly related to the yield of the wheat crop. As the value of these variables increased across the landscape, so did the yield. These variables are thus identified as important factors that should be considered in the selection of the transect benchmark and measured at the benchmark.

Table 2.6 - Relative deviation of average value for each landform element region from the average value for the entire transect (landscape) for 2006.

Land-scape Pos.	Soil Water	Soil P Supply Rate	Soil NO3-N Supply Rate	Soil NH4-N Ext	Soil NO3-N Ext	Soil P Ext.	Soil K Ext.	pH	EC	Grain Yield	Avg
	(%)	---- $\mu g/cm^2$ ----		------------ $\mu g/g$ ------------					ms/cm	kg/ha	
BS	-0.15	-0.15	-0.16	0.29	-0.08	-0.13	-0.2	-0.02	-0.50	0.03	-0.11
CF	-0.11	-0.03	-0.25	-0.31	-0.10	-0.23	-0.1	-0.01	-0.51	0.05	-0.16
CS	-0.08	-0.29	0.28	0.03	0.12	-0.21	-0.2	-0.07	-0.53	0.03	-0.09
DS	-0.08	-0.17	-0.08	-0.35	-0.03	-0.21	-0.1	-0.06	-0.64	-0.08	-0.18
FF†	0.15	0.16	0.06	-0.22	0.05	0.06	0.0	0.01	0.62	-0.02	0.09

†Best representative of the entire landscape.

Table 1.7 - The correlation coefficients of the soil variables as compared to grain yield for 2006.

Statistical Property	Soil Water	Soil P Supply Rate	Soil NO3-N Supply Rate	Soil NH4-N Ext	Soil NO3-N Ext	Soil P Ext.	Soil K Ext.	pH	EC
Correlation coefficient	0.126	0.354	0.235	0.048	0.255	0.050	0.045	0.048	0.088

Table 2.8 - Relative deviation of average value for each landform element region from the average value for the entire landscape of only those variables with correlation coefficient greater than R=0.1 for 2006.

Landscape Position	Soil Water Content	Soil P Supply Rate	Soil NO3-N Supply Rate	Soil NO3-N Extract
BS	-0.15	-0.15	-0.16	-0.08
CF	-0.11	**-0.03**	-0.25	-0.10
CS	**-0.08**	-0.29	0.28	0.12
DS	**-0.08**	-0.17	-0.08	**-0.03**
FF	0.15	0.16	**0.06**	0.05

2.4.7 Reselection of Benchmark According to Correlation Coefficient for 2006

If the benchmark were to be reselected again based on the correlation coefficient using only those variables having the most influence on yield, the variables with correlation coefficients greater than R=0.1 would be included (Table 2.7), such as soil phosphorus supply rate, nitrate supply rate, extractable nitrate and soil water content. If the relative deviations of only these four variables were used, the divergent shoulders would have the most variables with their averages

closest to the transect average (Table 2.8). This answer differs from the previously selected benchmark of flat foot slopes.

2.4.8 Comparison of 2005 and 2006

The current study is Year Two of a five year study to determine the stability of a benchmark in representing a variable landscape. In Year One, the project was carried out by Noorbakhsh et al. (2006) and the resulting benchmark was identified as backslope positions (BS). The same transect was used and the soil collecting, harvesting, sampling and data analysis techniques were identical. The only possible differences in the two years could be the crop type and the environmental conditions. Foot slopes are catchment areas that were usually high in nutrient and soil water content. Often these regions are high in mobile nutrients and water content. However the flat curvature of a flat foot slope means that water would neither accumulate (convergent) nor run off (divergent).

The second benchmark selection in this study using key variables resulted to yield indicated divergent shoulders (DS) as the ideal sampling position. Although it is not the same as the back slopes chosen by Noorbakhsh et al. (2006), divergent shoulders are found in the same region of the landscape (Figure 2.1). Divergent shoulders are neither extensively eroded like the convergent shoulder slopes nor are they the site of accumulation like convergent foot slopes. Divergent shoulders may be a more logical selection for a benchmark location. The findings in Year Two agree somewhat with Year One because the chosen landscape positions lie along the same slope (Figure 2.1). It is likely that these two landscape positions would have similar soil properties.

2.5 Conclusion

Of the soil properties measured across the transect, pH was the most strongly correlated with yield (inverse correlation), followed by soil organic carbon, soil water content, extractable K and nitrate and phosphate supply rates. The landform element with soil properties measured that most closely approximated the average across the entire landscape was the back slope for 2005 and divergent slope for 2006. The benchmark selected for the research transect at Central Butte, Saskatchewan differed between Year 2005 and Year 2006 of the study. The discrepancy could have been due to many factors, including crop nutrient requirements and relative importance of climate, soil moisture content, and soil properties, such as nutrient content, pH, and EC. These results suggest that it will be difficult to identify one single benchmark landform element that would work for all soil properties, crops and environmental conditions. A long term study may be required in order to determine a more dependable benchmark location. Included in the studies should also be an examination of the factors affected by the change in crop species.

2.6 References

Anderson, D.W. 1987. Pedogenesis in the grasslands and adjacent forests of the Great Plains. Adv. Soil Sci. 7: 53-93.

Bertsch, P.M. and G.W. Thomas. 1985. Potassium status of temperate region soils. In Potassium in agriculture. R.D. Munson (ed). ASA, CSSA, SSSA, Madison Wisconsin. pp 131-162.

Christiansen, E.A. 1979. The Wisconsinan deglaciation of southern Saskatchewan and adjacent areas. Can. J. Earth Sci. 16: 913–938.

Ellert, B.H. and J.R. Bettany. 1992. Temperature dependence of net nitrogen and sulfur mineralization. Soil Sci. Soc. Am. J. 56: 1133-1141.

Fiez, T.E., B.C. Miller and W.L. Pan. 1994. Assessment of spatially variable N fertilizer management in winter wheat. J. Prod. Agric. 7: 86-93.

Gregorich, E.G. and D.W. Anderson. 1985. Effect of cultivation and erosion on soils of four toposequences in the Canadian prairies. Geoderma, 36: 343-354.

Hanna, A.Y., P.W. Harlan, and D.T. Lewis. 1982. Soil available water as influenced by landscape position and aspect. Agron. J. 74: 999-1004.

Hendershot, W.H., H. Lalande, and M. Duquette. 1993. Soil reaction and exchangeable activity. In Soil sampling and methods of analysis. M.R. Carter (ed). Lewis publishers, Boca Raton. pp 141.

Jowkin,V. and J.J. Schoenau. 1998. Impact of tillage and landscape position on N availability and yield of spring wheat in the Brown soil zone in southwestern Saskatchewan. Can. J. Soil Sci. 78: 563-572.

Keeney, D.R. and D.W. Nelson. 1982. Nitrogen-inorganic forms . In A.L. page, R.H. Miller and D.R. Keeney (Eds). Methods of soil analysis: part 2, chemical and microbiological properties. Agronomy Mono. 9, A.S.A. Madison, W I., USA pp. 643-698.

Malo, D.D. and B.K. Worcester. 1975. Soil fertility and crop responses at selected landscape positions. Agron. J. 67: 397-401.

McConkey, B.G., D.J. Ulrich, and F.B. Dyck. 1996. Slope position and sub-soiling effects on soil water and spring wheat yield. Can. J. Soil Sci. 77: 83-90.

Moulin, A.P., D.W. Anderson, and M. Mellinger. 1994. Spatial variability of wheat yield, soil properties and erosion in hummocky terrain. Can. J. Soil Sci. 74: 219–228.

Pennock, D.J., B.J. Zebarth, and E. DeJong. 1987. Landform classification and soil distribution in hummocky terrain. Saskatchewan, Canada. Geoderma, 40: 297-315.

Qian, P. and J.J. Schoenau. 1995. Assessing nitrogen mineralization from soil organic matter using anion exchange membranes. Fert. Res. 40: 143-148.

Qian, P. and J.J. Schoenau. 2005. Use of ion exchange membrane to assess nitrogen supply power of soils. J. Plant Nutr. 28: 2193-2200.

Qian, P. and J.J. Schoenau. 2002. Practical applications of ion exchange resins in agricultural and environmental research. Can. J. Soil Sci. 82: 9-21.

Qian, P., J.J. Schoenau, and R.E. Karamanos. 1994. Simultaneous extraction of available phosphorus and potassium with a new soil test: A modification of Kelowna extraction. Commun. Soil Sci. Plant Anal. 25: 627-635.

Richardson, J.L., L.P. Wilding and R.B. Daniel. 1992. Recharge and discharge of ground water in aquic conditions illustrated with flownet analysis. Geoderma, 53: 65-78.

Roberts, T.L., J.W.B. Stewart and J.R. Bettany. 1985. The influence of topography on the distribution of organic and inorganic soil phosphorus across a narrow environmental gradient. Can. J. Soil Sci. 65: 651-665.

Sandovel, F.M., C.W. Carlson, R.H. Mickelson and L. Boriz. 1961. Effect of run-off penetration and leaching water on a saline soil. Can. J. Soil Sci. 41: 207-217.

Schoenau, J.J. and J.J. Germida. 1992. Sulphur cycling in upland agricultural systems. In Sulphur cycling on the continents. R .W. Howarth, J. W. B. Steward, and M. V. Ivanov (eds.). John Wiley & Sons Ltd., Chichester, UK, pp. 261–277.

Sinai, G., D. Zaslavsky, and P. Golany. 1981. The effect of soil surface curvature on moisture and yield - beer sheba observation. Soil Sci. 132: 367-375.

Stevenson, F.C., J.D. Knight and C. van Kessel. 1996. Dinitrogen fixation in pea: controls at the landscape and micro-scale. Soil Sci. Soc. Am. J. 59: 1603-1611.

Tallon L. and B.C. Si. 2004. Representative soil water benchmarking for environmental monitoring. J. Int. Informatics 4: 31-39.

Vachaud, G., A. Passerat De Silans, P. Balabanis, and M. Vauclin. 1985. Temporal stability of spatially measured soil water probability density function. Soil Sci. Soc. Am. J. 49: 822-828.

Verity, G.E. and D.W. Anderson. 1990. Soil erosion effects on soil quality and yield. Can. J. Soil Sci. 70: 471-484.

Whitman, C.E., J.L. Hatfield, and R.J. Reginato. 1985. Effect of slope position on the microclimate, grown and yield of barley. Agron. J. 77: 663-669.

Study III. Topographic Indices and Yield Variability in a Rolling Landscape of Western Canada

3.1 Summary

Understanding the relationships between topographic indices and crop yield variability is important for soil management and crop production in rolling landscape. The objective of this study was to examine how topographic indices relate wheat yield under two topographic and weather conditions in the Canadian prairies. The study was conducted at Alvena and Hepburn, Saskatchewan, Canada. The landscapes of the two sites are classified as hummocky and the dominant soil type is an Aridic Ustoll. The relationships between yield, topography, soil, and weather were analyzed using wheat (*Triticum aestivum L.*) grain yield from Alvena for 2001 (dry year) and 2004 (wet year) and Hepburn fields in 1998 (dry year). Topographic/soil indices included relative elevation (RE), wetness index (WI), upslope length (UL), curvature (CR), soil organic matter (OM), and soil moisture storage (MS) before seeding. The results indicated that, in drier than normal years, the correlation coefficients between UL and grain yield are 0.79 for the typical rolling landscape (Alvena) in 2001 and 0.73 for shallow gentle rolling landscape (Hepburn) in 1998. In the wet year (2004), the relationship between yield and topographic/soil attributes was not as strong as in dry years. Therefore, UL is the best yield indicators for the two landscapes in drier than normal years, while all topographic indices are not highly correlated to crop yield in wet years. Those topographic indices seem useful in identifying the yield variability and delineating the proper management zone.

3.2 Introduction

In the prairies of western Canada, hummocky landscapes constitute the majority of cultivated land. Due to loss and redistribution of topsoil and moisture from upper to lower slope, crop yield showed strong spatial variability in these landscapes (Halvorson and Doll 1991; Kravcheko and Bullock 2000; Walley et al. 2001; Pennock et al. 2001). The spatial variability can be attributed, in part, to topographic attributes (Si and Farrell 2004; Zeleke and Si 2004; Kaspar et al. 2004).

Topographic indices include relative elevation, slope, surface curvature, upslope length or contribution area and flow accumulation (Kravcheko and Bullock 2000). The effects of those topographic indices on crop yield were variable for different climatic and soil conditions. Ciha (1984), analyzing wheat yields from individual plots located at toe, concave, middle, convex, and interfluvial sites, found that landscape positions were a significant yield affecting factor. Timlin et al. (1998) showed surface curvature was a useful parameter for describing relationships among yield, topography, and weather on a 280-m by 150-m field plot. Zeleke and Si (2004) suggested that UL (upslope length) was the best indicator of grain yield and biomass of wheat at any scale. Because topographic indices are permanent spatial factors affecting crop yield and are easy and less costly to obtain compared to measurement of more dynamic soil properties, it is very important and valuable to examine their effects on crop yields for fertilizer application and site-specific management in precision faming.

The effect of those topographic indices on crop yield often depends on weather, particularly the precipitation. In semi-arid or arid regions where potential evapotranspiration is much larger than the total precipitation, soil water is the major limiting factor for crop production. Furthermore, the timing and intensity of the precipitation are generally out of phase with the water requirement

of the crop. The effect of precipitation (snow and rainfall) on crop yield is further enhanced by its interactions with terrain attributes and soil properties (Timlin et al. 1998; Kasper et al. 2004). However, the relationships between weather conditions, topography and yield reported in literature are rather contradictory (Kravcheko and Bullock 2000). Halvorson and Doll (1991) observed less influence of topography on yield in a dry year than in a wet year. Conversely, Simmons et al. (1989) reported the greatest influence of topography on yield in dry years. This contradiction can be explained in part by differences in soil and climatic conditions in which the experiments were conducted.

In rolling landscapes of semiarid prairie of western Canada we would expected that topographic indices are useful indicators of wheat yield either in drier than normal years or in wet years. However, poor understanding on which topographic indices best describe crop yield and how the relationships between crop yield and topographic indices change with weather conditions, led to the objectives of this study: (1) to examine how the topographic indices affect wheat yield under different topographic conditions and (2) to investigate how topographic indices affect wheat yield under different weather conditions.

3.4 Materials And Methods

3.4.1 Site description

The study was conducted using data from two agricultural fields, one located at Alvena (49°44′N lat, 107°35′W longitude) and the other located at Hepburn (52°25′N lat,106°41′W long), Saskatchewan, Canada. The National Climate Data and Information Archive, Canada provided the monthly climate data from the nearest weather recording station to the fields. The long-term (1971-2001) average annual precipitation is 371.5 mm, which primarily falls in the winter and/or spring (snow) and summer (rainfall). The average temperature is 4.5℃ and potential evapotranspiration reaches 624 mm yr^{-1}. The annual precipitation was 260 mm for Alvena in 2001 and 523 mm in 2004, and was 287 mm for Hepburn in 1998. Compared with the long-term average, it was drier than average in 1998 for Hepburn and very dry for Alvena in 2001, while it was very wet in 2004. The precipitation has a very different monthly distribution in 1998, 2001 and 2004. The average monthly precipitation from April through September for 1998, 2001, 2004 and long-term (1971-2001) are shown in Fig. 3.1

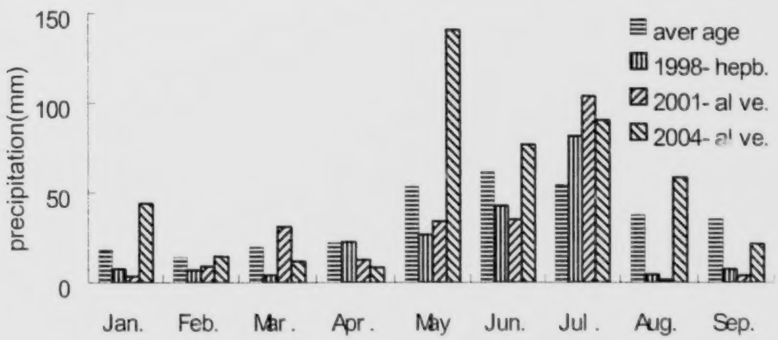

Fig. 3.1. Monthly precipitation data for January through September in studied sites.

The landscape is classified as hummocky and the dominant soil type is Aridic Ustoll. The Alvena site was generally under summer fallow-wheat or Canola rotation. It was under summer fallow in 2000, and 2002. The field was planted with spring wheat in 2001 and 2004, and canola in 2003. For the Hepburn site, soils on slopes and upper-levels were dominantly Typic Haploborolls with significant inclusions of Typic Aquolls in depressional areas. The field had been cropped with wheat for the previous 2 years using zero tillage (Walley et al. 2001). Spring wheat was seeded on April 26, 2001 and on May 10, 2004 at the Alvena site and May 15, 1998 at the Hepburn site. All necessary management procedures were implemented as needed during the growing season. The crop was harvested on Aug. 30, 2001 and Sept. 10, 2004 for Alvena and Sept. 3, 1998 for Hepburn. A 1.0-m^2 area along the transect was selected at 6-m intervals for the Alvena site and 3-m intervals for the Hepburn site and the wheat was hand-harvested to determine the total aboveground biomass and grain yield. The yield was then converted to kilogram per hectare (kg ha^{-1}). To avoid unnecessary border effects on the grain yield some data points at both ends of the transect were removed and only 96 points were used in the correlation analysis. The wheat yield statistics for 96 points along the transect are shown in Table 3.1. In order to describe the grain yield in different positions along the transect at Alvena, we plotted four types of landform complex: knoll (the points on convex with 1m difference of elevation), depression (the points on concave with 1m difference of elevation), back slope (the points between knoll and depression where the slope dose not face the sun), and front slope (the points between knoll and depression where the slope faces the sun). Detailed description of the sites as well as the sampling procedures is reported in Walley et al. (2001) and Si and Farrell (2004).

Table 3.1. Statistics of spring wheat yield data

Fields	years	Grain yield Mean	SD	Min.	Max.
		kg ha^{-1}			
Hepburn	1998	1560	627	612	3106
Alvena	2001	1332	878	140	4480
Alvena	2004	2667	723	1246	4379

3.4.2 Topographic indices and soil properties measurement

A laser theodolite was used to measure elevations at all points where the crop yield was sampled. Additional elevation and horizontal distance measurements were taken perpendicular to the transect. These elevation measurements allow for precise calculation of surface curvature, upslope length, and wetness index at any point along the transect. Surface curvature (CR) is the rate of change of elevation gradient in the direction of slope. Negative curvature corresponds to concave surface and is characteristic of depressions, while positive curvature corresponds to convex surface, or hills. CR can be calculated from the elevations using the following approximations (Sinai et al. 1981; Pennock et al. 1994; Shary et al. 2002)

$$CR \approx \frac{\partial^2 Z}{\partial X^2} + \frac{\partial^2 Z}{\partial Y^2} \qquad [3.1]$$

Numerically, CR was approximated as

$$CR = \frac{Z_{i+1,j} + Z_{i-1,j} - 2Z_{i,j}}{\Delta X^2} + \frac{Z_{i,j+1} + Z_{i,j-1} - 2Z_{i,j}}{\Delta Y^2} \qquad [3.2]$$

where Z is elevation at a point and i and j represent the indices for the x and y coordinates of a point, respectively.

The wetness index was used as an indicator of water accumulation in an area of the landscape where water is likely to concentrate through runoff processes (Beven and Kirkby 1979). The wetness index is defined as

$$WI = \ln\left(\frac{\gamma}{\tan\beta}\right) \qquad [3.3]$$

where γ is the contribution area per unit contour length and $\tan\beta$ is the local terrain slope of the landscape elements. Because the two landscapes are predominantly undulating, we assume that the contour lines are perpendicular to the transect. Therefore, the contributing area is the upslope length, calculated as the distance from a given point in the landscape to the highest elevation point along the transect. Hereafter, we refer to γ as the upslope length.

At the Alvena site, undisturbed soil samples (0 to 5cm) were collected using a ring. Two sets of subsamples were used for determination of soil texture by the hydrometer method (Gee and Bauder 1979) and organic C content using method of Wang and Anderson (1998). At the Hepburn site, the soil water contents were measured, using the gravimetric method, in increments of 0 to 15, 15 to 30 and 30 to 60 cm in every point before planting and the soil water storage was calculated from depth 0 to 60 cm. Pearson correlation coefficients (r) were calculated from topographic attributes and soil properties (Table 3.2).

Table 3.2. Statistics of selected topographic and soil attributes for the Alvena and Hepburn sites

Indices	Mean	SD	Min.	Max.
		Alvena field		
Upslope length (m)	6.37	4.73	0.50	19.00
Wetness index	4.87	1.02	2.32	7.33
Relative elevation (m)	-2.52	1.88	-5.76	0.85
Surface curvature(m^{-1})	-0.0026	0.0273	-0.0445	0.0866
Organic C ($g\ kg^{-1}$)	21.6	6.8	10.3	38.4
Clay content ($g\ kg^{-1}$)	296.4	50.6	203.6	410.7
		Hepburn field		
Upslope length (m)	4.91	3.69	0.5	15.0
Relative elevation (m)	0.98	0.35	0.41	1.69
Wetness index	4.63	1.16	1.68	8.34
Soil moisture (mm)	126.1	33.9	74.1	207.6

3.5 Results And Discussion

3.5.1 Yields variability and field surface configurations

Though both fields are classified as rolling landscapes, there are large differences in their field topographic patterns (Table 3.2 and Figure 3.2). There are two large depressions centered at 90 and 430 m and a few small depressions centered at 200, 300, and 570 m along the transect at the

Alvena site; there are three large, shallow depressions at 50, 230, and 450 m and three obvious knolls at 140, 390, and 558 m along the transect in Hepburn. Consequently, topographic indices are also different. However, there are some common features in the two fields; the measured grain yield, elevation, upslope length, wetness index, soil organic matter, and soil water storage before seeding all exhibit a similar trend; large values in the depressions and small values on the knolls. Correlation coefficients *(r)* between yields, topographic indices, and soil properties in the two fields in 2001 are shown in Table 3.3.

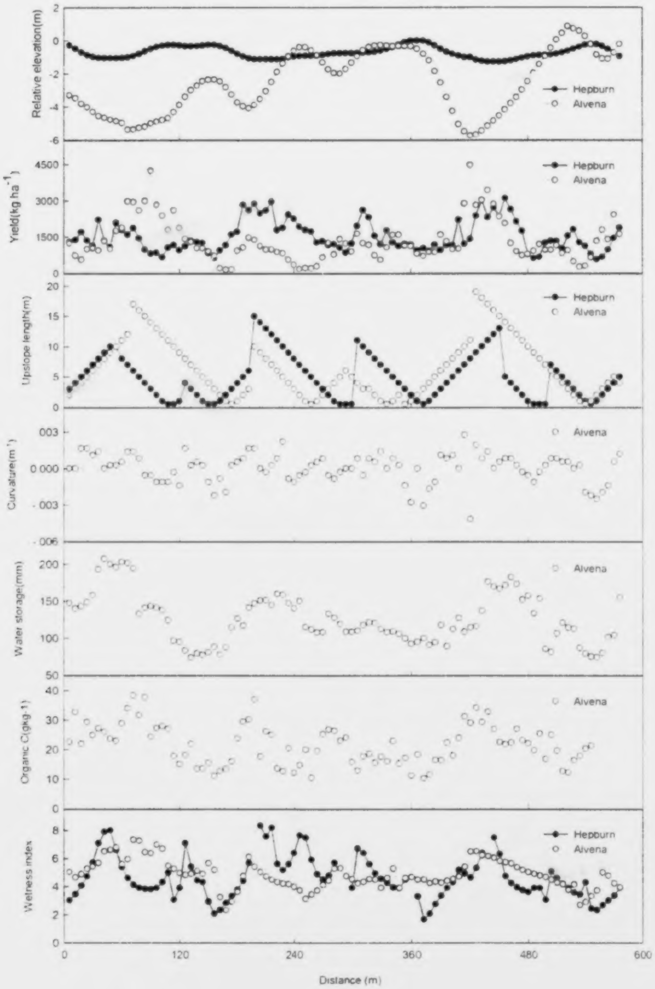

Figure 3.2. Measured elevations and grain yields along the two transects from the two fields in 1998 and 2001, along with upslope length, surface curvature, wetness index; Also shown are the measured soil properties, soil organic matter at Alvena and soil water storage before planting at Hepburn.

Table 3.3. Correlation coefficients (r) between yields, topographic indices and soil properties for the Alvena and Hepburn sites

Indices	Upslope	Elevation	Wetness	Curvature	Organic C	Clay cont.
		Alvena site				
Grain yield	0.79	-0.63	0.73	-0.14	0.49	-0.09
Upslope	---	-0.81	0.83	-0.14	0.63	-0.11
Elevation		---	-0.72	-0.05	-0.67	-0.07
Wetness			---	-0.23	0.59	-0.06
Curvature				---	-0.15	0.28
Organic C					---	-0.26
		Hepburn site				
Indices	Upslope	Elevation	Wetness	Curvature	Soil water storage	
Grain yield	0.73	-0.68	0.60	(0.41)	0.47	
Upslope	---	-0.69	0.79	(0.44)	0.54	
Elevation		---	-0.63	(-0.52)	-0.71	
Wetness			---		0.50	

Wheat grain yields were positively correlated to upslope length and correlation is highest among all the topographic indices for both fields. This is consistent with Si and Farrell (2004) and Zeleke and Si (2004). Grain yields were negatively correlated with relative elevations in the Hepburn and Alevna fields. The correlation coefficients (r_{y-e}) were -0.62 Alvena and -0.68 for Hepburn. In general, these negative correlations agree with the common experience in this region and many other researchers. Kravchenko and Bullock (2000) observed negative correlations between corn yield and relative elevation, slope, and curvature, especially in dry environments. Relative elevation had the best correlation with yield in their study. Kaspar et al. (2004) showed that in the four years with less than normal growing season precipitation, corn yield was negatively correlated with relative elevation, slope, and curvature. Their study was conducted in Boone County, Iowa, USA. Manning et al. (2001) draw similar conclusion in their spring wheat experiment located on undulating glacial till soils near Miniota, Manitoba, Canada.

The correlation of wheat grain yield with upslope length and relative elevation is likely resulted from the movement of soil water from high elevation to low elevation, and the formation of snow drift. Surface structure determines the direction and force of water movement in the field and controls the soil moisture conditions. In addition, in these cultivated landscapes, erosion and tillage translocation may effectively reduce the fertility of soils on knolls and enhance the fertility of soils in depressions (Lobb and Kachanoski 1999; Miller et al. 1998). There was a strong positive correlation between grain yield and upslope length along the transects. This is because water is the limiting factor for crop production in semiarid regions. The number of heads is determined in the first month of wheat growth especially for spring wheat. Water stress in spring can significantly reduce the number of heads per unit area, resulting in a loss of the wheat yield (Si and Farrell 2004; Yang et al. 1998). In general, spring soil water storage at a given point in the landscape is closely related to the area contributing snow and water to the point (the definition of upslope length). At the Hepburn site, however, there was only a mild correlation between upslope length and soil water storage before seeding (r=0.54). This may be because depressions in Hepburn are relatively shallow and precipitation before seeding in 1998 is relatively small (Figure 3.1), resulting in little snow redistribution. Though the total precipitation

is only 77% of the long term average of annual precipitation, the growing season (April to September) precipitation is 95% of the long term average of growing season precipitation (Figure 3.1). Any topographic and soil attributes that contribute to water accumulation in the landscapes, such as upslope length, wetness index, and soil organic matter, were positively correlated to the increases in grain yield (Table 3.3 and Figure 3.2.). However, there was a weak correlation between soil surface curvature and grain yield ($r = -0.14$) in this study. This is because curvature reflects the topography shape (convex or concave), not the size of depressions (Si and Farrell 2004). However, the correlation coefficient was lower than that reported by Kaspar et al. (2004) and Kravchenko and Bullock (2000).

3.5.2 Yields variability and drier and/or wet years

It was a very wet year in 2004; the annual precipitation and rainfall during the growing season (April to September) were 522.8 mm and 396.0 mm, respectively, about 40.7% and 49.7% higher than the long term averages and 2.01 and 2.08 times the 2001 levels (Figure 3.1). As a result, the topography-yield relationships for the same crop (spring wheat) in the same field (Alvena) were different under different weather conditions. The correlation coefficients between topographic and soil attributes and grain yields in 2001 and 2004 were shown in Table 3.4.

Table 3.4. Correlation coefficients between topographic and soil attributes, and yields in 2001 and 2004 for the Alvena site

	correlation coefficients (r)				
Years	Upslope-yield	Wetness-yield	Elevation-yield	Curvature-yield	Organic-yield
2001	0.7931	0.7340	-0.6252	-0.1416	0.4904
2004	-0.2925	-0.3087	0.5148	-0.3839	-0.4345

Correlation coefficients between wheat yield and topographic indices are not only different, but also have opposite signs for the two years (Table 3.4). This is consistent with the results of other researchers. For example, Kaspar et al. (2004) reported that the average corn yields of the two wet years were positively correlated with elevation and slope; the average corn yields of the four dry years were negatively correlated with relative elevation, slope, and curvature. Manning et al. (2001) observed that in 1997 during which the growing season precipitation was 37% below average, wheat median grain yield tended to increase with convergent character in the landscape (upper < mid < lower); in 1998, when the growing season precipitation was 62% above average, wheat median grain yield tended to decrease with convergent character in the landscape (upper > mid > lower). From the magnitude of correlation between soil-landscape indices and grain yield (Table 3.4), the absolute value of correlation coefficient (r upslope-yield) was the maximum in dry year (2001) and the minimum in wet year (2004). This is not surprising, given that upslope length is a measure of water accumulation at a point in the landscape. Soil water content is the most important limiting factor for crop production and so upslope has a large and positive effect on the yield in a dry year. However, water is not the limiting factor for crop growth in wet year, so upslope length has little effect on the crop yield.

Though weather conditions were clearly the dominant controlling factor for the year-to-year yield differences in semiarid regions, the landscape/soil features influenced the redistribution of runoff water and rainfall, and hence the soil moisture conditions and crop yields. The diversiform

landscape along the transect of Alvena was delineated to four landform complex as: knoll, depression, back slope and front slope using point elevation and direction of slope. The grain yield statistics on different landform complexes in Alvena in 2001 and 2004 are given in Table 3.5. The following conclusion can be drawn: First the average wheat grain yield of the field in 2004 doubled that of 2001 due to the improvement of the soil moisture conditions. Furthermore, although water shortage is a permanent problem in semiarid regions, semiarid regions still need to deal with unusual excess water in different months and years, especially in areas with a rolling landscape and closed depressions (Kaspar et al. 2004; Manning et al. 2001) and/or poorly drained soils (Ginting, et al. 2003; Zebarth and Jong. 1989). Finally, there was a huge gap in crop yields of different landform complexes, suggesting opportunity for site-specific management practices (Kaspar et al. 2004; Pennock et al. 2001). In the dry year (2001), the order of wheat grain yield from high to low was: depression > back slope ≈front slope > knoll in the dry year (2001); and front slope > knoll > back slope > depression in the wet year (2004). Though the correlations between relative elevation and grain yield in dry and wet years were opposite (Table 3.4), the yields in different landform complexes in the two years were not entirely opposite. In the dry year (2001), the lowest yield zone was located on the knoll, however, the highest yield zone in wet year (2004) was not on the knoll but on the front slope, probably related to the soil fertility or other factors.

Table 3.5. Wheat grain yields averaged on landform complex in Alvena field

Landform	2001				2004			
Complex	Mean	Max.	Min.	SD	Mean	Max.	Min.	SD
		kg ha^{-1}				kg ha^{-1}		
Knoll	710.0	1590.0	140.0	427.1	2998.1	4210.0	1812.2	642.3
Back slope	1243.9	2880.0	650.0	531.6	2376.4	3820.0	1476.0	514.3
Front slope	1273.7	2860.0	340.0	891.1	3121.1	4378.8	1980.0	581.8
depression	2228.3	4480.0	770.0	1046.0	1956.6	2632.2	1246.4	365.8
Whole field	1332.1	4480.0	140.0	877.5	2666.6	4378.8	1246.4	723.2

Bevan and Kirkby (1979) and other research in hydrology showed that wetness index is a good indicator of water excess in humid regions. Si and Farrell (2004) and Zeleke and Si (2004) showed that upslope length is best correlated to wheat grain yield in a semiarid zone during a dry year. To the best of our knowledge, this study is the first study showing that upslope length is the best crop yield indicator in semiarid zones in dry years, while in wet years, the upslope length, like other topographic indices, are not good indicator of crop yield variability in a field. We believe that upslope length would be a good indicator of crop yield in average precipitation years in semiarid zones. However, more research is needed to be conclusive.

3.5 Conclusions

The results of this study suggest that there are different magnitudes of correlation between topographic/soil indices and wheat grain yield in different fields and during different years in the rolling landscape of central Saskatchewan, Canada. The soil moisture condition is the main factor controlling wheat grain yield variability and influencing the significance of topographic/soil indices in semiarid regions. In drier than normal years, upslope length is the best yield determining factor of all topographic/soil indices in the study. It has strong correlation with

grain yield and is closely related to other topographic/soil indices in either a typical rolling landscape (Alvena) or a shallow gently rolling landscape (Hepburn). Relative elevation can be ranked second. In wet years, the relationship between yield and topographic/soil attributes was not as strong as in dry years. Topographic/soil indices seem useful for identifying the yield variability and forming proper management zone.

3.6 References

Anderson, D.W. 1987. Pedogenesis in the grasslands and adjacent forests of the Great Plains. Adv. Soil Sci. 7: 53-93.

Bertsch, P.M. and G.W. Thomas. 1985. Potassium status of temperate region soils. In Potassium in agriculture. R.D. Munson (ed). ASA, CSSA, SSSA, Madison Wisconsin. pp 131-162.

Beven, K.J., and M.J. Kirkby. 1979. A physically-based, variable contributed area model of basin hydrology. *Hydrol. Sci. Bull.* **24**: 43-69.

Ciha,A.J.1984. Slope position and grain yield of soft white winter wheat. *Agron.J.***76**: 193-196.

Gee, G.W., and J.W. Bauder. 1979. Particle size analysis by hydrometer: A simplified method for routine textural analysis and a sensitivity test of measurement parameters. *Soil Sci. Soc. Am. J.* 43: 1004-1007.

Ginting, Daniel, John F. Moncrief, and Satish C. Gupta. 2003. Performance of a variable tillage system based on interactions with landscape and soil. *Precision Agriculture*. **4**: 19-34.

Halvorson, G.A. and E.C. Doll. 1991. topographic effects on spring wheat yield and water use. *Soil Sci. Soc. Am. J.* **55**: 1680-1685.

Kaspar, TC, Pulido, DJ, Fenton, TE, Colvin, TS, Karlen, DL, Jaynes, DB, Meek, DW 2004. Relationships of corn and soybean yield to soil and terrain properties. *Agron. J.* **96**(3): 700-709.

Kravchenko, A.N., and D.G. Bullock. 2000. Correlation of corn and soybean grain yield with topography and soil properties. *Agron. J.* **92**: 75-83.

Lobb, D.A., and R.G. Kachanoski, 1999. Tillage traslocation and tillage erosion in the complex upland landscapes of south western Ontario. *J.Soil and Tillage Research*. **51**: 317-330.

Manning, G., Fuller, L.G., Flaten, D.N. and Eilers, R.G. 2001. Wheat yield and grain protein variation within an undulating soil landscape. *Can. J. Soil Sci.* **81**: 459-467.

Miller, M.P., M.J. Singer, and D.R. Nielsen. 1988. Spatial variability of wheat yield and soil properties on complex hills. *Soil Sci. Soc. Am. J.* **52**: 1133-1141.

Pennock, D. J., Anderson, D. W. and de Jong, E. 1994. Landscape-scale changes in indicators of soil quality due to cultivation in Saskatchewan, Canada. *Geoderma*. **64**(1-2): 1-19.

Pennock, D.J., F. Walley, M. Solohub, B. C. Si, and G. Hnatowich. 2001. Topographically controlled yield response of Canola to nitrogen fertilizer. *Soil Sci. Soc. Am. J.* **65**: 1838-1845.

Shary, P.A., L.S. Sharaya, and A.V.Mitusov. 2002.Fundamental quantitative methods of land surface analysis. *Geoderma*. **107**: 1-3.

Si,B.C.,and R.E.Farrell.2004. Scal-dependent relationship between wheat yield and topographic indices:A wavelet approach. *Soil Sci. Soc. Am. J.* **68**: 577-587.

Simmons, F.W., D.K. Cassel, and R.B. Daniel. 1989. Landscape and soil property effects on coen grain yield response to tillage. *Soil Sci. Soc. Am. J.* **53**: 534-539.

Sinai, G., D. Zavlavsky, and P. Golany. 1981. The effect of soil surface curvature on moisture and yield Beersheba observations. *Soil Sci.* **132**: 367-375.

Timlin, D., Y. Pachepsky, V.A. Snyder, and R.B. Bryant. 1998. Spatial and temporal variability of corn yield on a hillslope. *Soil Sci. Soc. Am. J.* **62**: 764-773.

Walley F., D. Pennock, M. Solohub and G. Hnatowich, 2001. Spring Wheat *(Triticum aestivum)* Yield and Grain Protein Responses to N Fertilizer in Topographically Defined Landscape Positions. *Canadian J. Soil Sci.*, **81**: 505-514.

Wang, D., and D.W. Anderson. 1998. Direct measurement of organic carbon content in soils by Leco CR-12 carbon analyzer. *Commun.Soil Sci. Plant Anal.* **29**: 15-21.

Yang, C, C.L. Peterson, G.J. Shropshire, and T.Otawa. 1998. Spatial variability of field topography and wheat yield in the Palouse region of the Pacific Northwest. *ASAE* **41**: 17-27.

Zebarth, B.J., and E. de Jong. 1989. Water flow in a hummocky landscape in Central Saskatchewan, Canada, I. Distribution of water and soils. *J. Hydrol. (Amsterdam)* **107**: 309-327.

Zeleke, T.B. and Bing C. Si. 2004. Scaling properties of topographic indices and crop yield: multifractal and joint multifractal approaches. *Agron. J.* **96**: 1082-1090.